| REPORT DOCUMENTATION PAGE | Form Approved<br>OMB No. 0704-0188 |
|---|---|



| 1. AGENCY USE ONLY (Leave Blank) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | 1994 | Conference Proceeding |

**4. TITLE AND SUBTITLE**
Coherent Laser Radiometric Measurements of LEO Satellites.

**5. FUNDING NUMBERS**

**6. AUTHOR(S)**
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**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
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**8. PERFORMING ORGANIZATION REPORT NUMBER**
PL-LI 94-28

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**



**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**
COSATI CODE(S): 9/03; 14/02

**12a. DISTRIBUTION / AVAILABILITY STATEMENT**
~~Pub. in Proceedings of 1994 Space Surveillance Workshop, Lexington, Massachusetts.~~



**12b. DISTRIBUTION CODE**
A

**13. ABSTRACT (Maximum 200 words)**

The US Air Force recently completed the Floodbeam Experiment, recording the first ever coherent laser returns from non-augmented low-earth orbit satellites. Illumination was performed during terminator periods (the satellite was sunlit while the experiment site was in darkness). This allowed use of a visible tracking system for good performance against distant and dim targets. A coherent, pulsed, near-infrared laser was used to illuminate 35 different satellites at the Starfire Optical Range (SOR), near Albuquerque, NM. The 1 meter clear aperture Starfire Beam Director (SBD) was used to transmit pulses at 1/7 Hsubz repetition rate. A low-noise IR camera collected speckle returns at a re-imaged pupil plane of the Starfire 1.5 meter telescope. ABS: Results include first ever resolved satellite whole-body speckles. Radiometric data are consistent with calculations, and exhibit occasional glinting. Depolarization data were obtained by comparing energy in the returns corresponding to the outgoing linear polarization in addition to the cross polarization. Depolarization data represent losses to a coherent imaging system.



**14. SUBJECT TERMS**
LEO (low earth orbit); lasers; radiometry; satellite tracking systems; radiometric measurements

**15. NUMBER OF PAGES**
8

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | SAR |

Proceedings of 1994 Space Surveillance Workshop, Lexington, MA 1994.
PL/LIMI

PL-LI 94-28

# Coherent Laser Radiometric Measurements of LEO Satellites

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## Introduction

The US Air Force Phillips Laboratory recently completed the Floodbeam Experiment, recording the first ever coherent laser returns from non-augmented, low earth orbit satellites. Illumination was performed during terminator periods (the satellite was sunlit while the experiment site was in darkness). This allowed use of a visible tracking system for good performance against distant and dim targets.

A coherent, pulsed, near-infrared laser was used to illuminate 35 different satellites at the Starfire Optical Range (SOR), near Albuquerque, NM. The 1 meter clear aperture Starfire Beam Director (SBD) was used to transmit pulses at a 1/7 Hz repetition rate. A low-noise IR camera collected speckle returns at a re-imaged pupil plane of the Starfire 1.5 meter telescope. Results include first ever resolved satellite whole-body speckles. Radiometric data are consistent with calculations, and exhibit occasional glinting. Depolarization data were obtained by comparing energy in the returns corresponding to the outgoing linear polarization in addition to the cross polarization. Depolarization data represent losses to a coherent imaging system.

## Laser Illuminator

Laser illuminator requirements included substantial energy per pulse, excellent beam quality, and superb coherence. A 1.3 micron wavelength, photolytic (flashlamp pumped) iodine laser was developed in-house at the Phillips Laboratory that met the requirements. Coherence length was demonstrated to be greater than 45 meters using Mach-Zehnder interferometry. The coherence length had to be substantially longer than the greatest dimension of a typical target so that a fully developed speckle pattern would be produced by reflections from all observable points on a target.

Laser pulse energy exceeded 50 Joules on a routine basis. More energy was available, but the pulse shape deteriorated due to development of an initial gain-switched spike. Additionally, flashlamps would fail as they were driven to excessive voltages. Energy was also somewhat restricted by the necessity to extract useful energy in a minimal pulse length. Many hardware modifications were performed to reduce the pulse length to 7 microseconds. Satellite orbital velocities inherently produce speckle smearing, reducing the quality of the captured speckle patterns. Even at 7 microseconds, our data show these effects.

The laser's pulse repetition rate was 1/7 Hertz. The longitudinal flow design restricts higher repetition rates without severe degradation in beam quality. At 1/7 Hertz, the laser beam quality was better than 1.5 times diffraction-limited. This repetition rate still allowed typically 15 to 20 shots per engagement.

## Transmitter/Tracker System

The transmitter system was required to accurately track satellites as dim as 10th visual magnitude ($M_V = 10$) and place the illumination beam on the target with less than 5 µrad rms boresight and jitter error. The system also had to preserve the excellent beam quality and linear polarization of the high power beam. A large variety of satellites and rocket bodies were illuminated during the experiment. In all cases the objects were classified as "dead" and appropriate permission was obtained from the USSPCM Laser Clearing House.

A schematic of the experiment is shown in Figure 1. The 1.3 micron laser beam was directed to the satellite using the Starfire Beam Director. Although the director has a 1 meter clear aperture, tracking and illumination was limited to a 28 cm diameter aperture. The transmitter/tracker system used three different wavelength bands for propagation, tracking, and alignment. The near-infrared band is used for transmitting the high power beam. Care was taken

to maintain the high degree of linear polarization of the outgoing beam through the use of (1) a fully reflective path at near normal incidence, and (2) polarization preserving coatings on the optics.

Sunlight reflected from the target in the wavelength band between 600 nm and 900 nm was used for target fine tracking. The track sensor employed a Gen III intensifier and a Hamamatsu position-sensitive photomultiplier tube (PMT). The signals from the PMT closed the tracker loop around the beam steering mirror (BSM). Three track bandwidths were utilized: 3 Hz for very dim targets, 17 Hz for normal operation, and 75 Hz for bright targets. The target set ranged from approximately $M_V = 4$ at the brightest, to less than $M_V = 10$ (which were not trackable). Individual objects varied in brightness over the course of a pass and from night to night due to changing viewing geometry, variable weather conditions, and changing aspect angles.

System alignment, boresight and point-ahead were achieved using a 458 nm wavelength alignment beam that was injected into the iodine laser cavity to mimic the high power beam mode. The alignment beam regurgitated from the cavity was then sensed to estimate the position and pointing of the high power beam. The point-ahead angle necessary to hit the satellite was calculated from the orbit trajectory and digitally added to the point-ahead control loop. The alignment system was one of the limiting factors in determining the laser repetition rate. Approximately five to seven seconds were required for the laser cavity to settle after each laser pulse before the alignment laser was stable enough to accurately predict the path of the high power beam.

An operations summary follows: Targets were selected during pre-mission planning. Ephemeris data and predictive avoidance times were loaded into the mount control computer prior to the pass. Rough pointing was accomplished by the mount controller. The target was normally acquired in the wide field-of-view (FOV) camera which has a FOV of approximately 4 milliradians. The mount operator updated the object's position to center it in the 300 microradian narrow FOV camera. The tracker operator then centered the object in the 60x80 microradian tracker FOV and closed the fine track loop.

Laser firing was initiated once fine track was established and the safety system showed all clear. The safety system consisted of many interlocks to make sure that the laser cannot fire unless all systems are go and all the dangerous areas are clear. The final safety check was an aircraft watch operator holding down a ready-to-fire button.

## Receiver System

The receiver system was required to record a pupil-plane image of the returning speckle patterns. The system had to adequately sample the pattern spatially, determine the amount of depolarization of the light induced by the target, and allow accurate radiometry values to be obtained from the data. The polarization measurement was important since depolarization effectively amounts to a loss in return signal when measuring a linearly polarized, coherent speckle pattern.

Referring to Figure 1, the returning 1.3 micron photons were collected by the 1.5 m telescope at the SOR and a low-noise IR camera recorded the speckle patterns. The receiver optical system actually separated the linearly polarized light that was aligned with the transmit beam from the light scattered into the cross polarization. The optical system also employed a zoom lens that adjusted the pupil image magnification to ensure adequate spatial sampling of the return speckle pattern by the camera. The zoom system allowed a 3:1 magnification range. Accurate radiometric calibration of the receiver optical train and camera was completed in the laboratory before the system was fielded.

Coarse pointing was accomplished with the mount control system using an ephemeris model. The open-loop pointing of this mount was sufficient to keep the object within the FOV of the pupil-plane camera. The visible light focal-plane camera viewed an image of the target which was used by the mount operator to center and maintain the open-loop track on the target.

## Results

The Floodbeam experiment was designed to demonstrate the technologies necessary to do acquisition, pointing, tracking, and illumination of low earth orbit satellites. The primary goal of the experiment was to collect accurate radiometric measurements of a set of approved satellites. Additionally, an ambitious objective was to spatially sample the coherent returns to examine the statistical properties of the backscattered coherent laser speckle.

Figure 2 shows an example of the radiometric measurement made on a single satellite pass. The graph shows the total number of returned photons that reached the camera face. The collection aperture was the full 1.5 m diameter. As can be seen, the return varies across the entire pass showing the expected increase in return at the shortest ranges during the middle of the pass. The graph also shows some dramatic pulse to pulse variations which are probably primarily due to pointing and tracking jitter as well as changes in the target aspect.

An example of the speckle patterns collected for one of the larger targets is shown in Figure 3. The figure shows returns from five consecutive laser pulses near the middle of a particular pass. The patterns are all scaled to a common reference shown on the right of the figure. A few of the brightest speckles are slightly saturated in this display in an attempt to show the full detail of the speckle patterns. Visually, the pupil images appear speckled as one would expect for a coherent return. Initial analysis shows that the contrast in the patterns is also very high. The fringing pattern discernible at approximately 45 degrees to the right of vertical indicates that this particular satellite's longest dimension was oriented along that axis. Although not immediately obvious, the patterns are slightly smeared, approximately 1/4 to 1/2 of a pixel, due to the velocity of the speckle pattern and the 7 microsecond laser pulse. Analysis is currently underway to remove the effects of smearing.

Figure 4 shows some initial radiometric results for several classes or types of targets. The vertical axis is the total return reaching the camera face (as in Figure 2). Along the bottom axis, targets are grouped in seven classes that were thought to have similar backscatter cross-sections. The dark bars in the graph are average, maximum returns for a specific satellite. These values were obtained by finding the maximum return (single laser shot) for each pass of the given object and averaging these maximum values over all the engagements for that object. In other words, the dark bars represent the typical "best" shot of a given pass. The lighter bars are values calculated using a radiometric model that incorporates the system transmissions, estimated target cross-sections, laser beam quality, etc. The figure shows that in most cases the "best" shot returns are larger than the predicted returns, which is expected since the "best" shots may include glints or other advantageous phenomena such as momentary good seeing conditions. Only class 6 targets seem to show weaker returns than expected which suggests that the cross-sections of these targets are smaller than those used in our model. Further radiometric data reduction is underway.

## Conclusions

The experiment was extremely successful. Difficult problems were solved in establishing a new experimental facility at the Starfire Optical Range, while conducting an ambitious field experiment. Extensive radiometry and speckle pattern data will be useful in the development of new imaging concepts, especially for the Phillips Laboratory's Active Imaging Testbed, now under development.

## Acknowledgments

The authors would like to acknowledge the many people who were involved with the experiment and its development over the years: from the Phillips Lab Imaging Technology Branch Maj Paul Idell, Lt Col Shawn O'Keefe, Capt Ted Kreifels, Lt Donna Keating, Dr John Gonglewski, MSgt Pat Connoly, and Capt Bill Arrasmith; from the PL Laser Branch Dr. Vern Schlie and Dr Robert Rathge; from the PL Tracking Branch Dr. Sal Cusamano, Lt Ralph Galetti, and Capt John Mileski; from the PL SOR Division Capt Eric Stewart, SSgt Ben Knepper, and Dr Bob Fugate; from Hughes Aircraft Jim Kitchen, Gordon Lukesh, Mike Meline, Dennis Mansell, Joe Paranto, Calvin Barnard, Sylvia Rogers, Carla Neuman, and Terry Shirrod; from Rockwell Power Systems Steve Hanes, Jeff Baker, Bob Wilmot, Joe Blea, Victor Gamiz, Robert Babnick,

Joe Rae, and Bruce Crawford; from BDM Roger Holt, Nils Hochhauser, Charly Tipton, Russ Smith, Jerry James, and Cathy VanBerg; from S Systems Ted Turner and Karl Shrader; from tOSC John Belsher and Glenn Tyler. The authors realize that many more people were indispensable in getting this experiment off the ground. We regret not being able to mention everyone, but offer our sincere thanks to all.

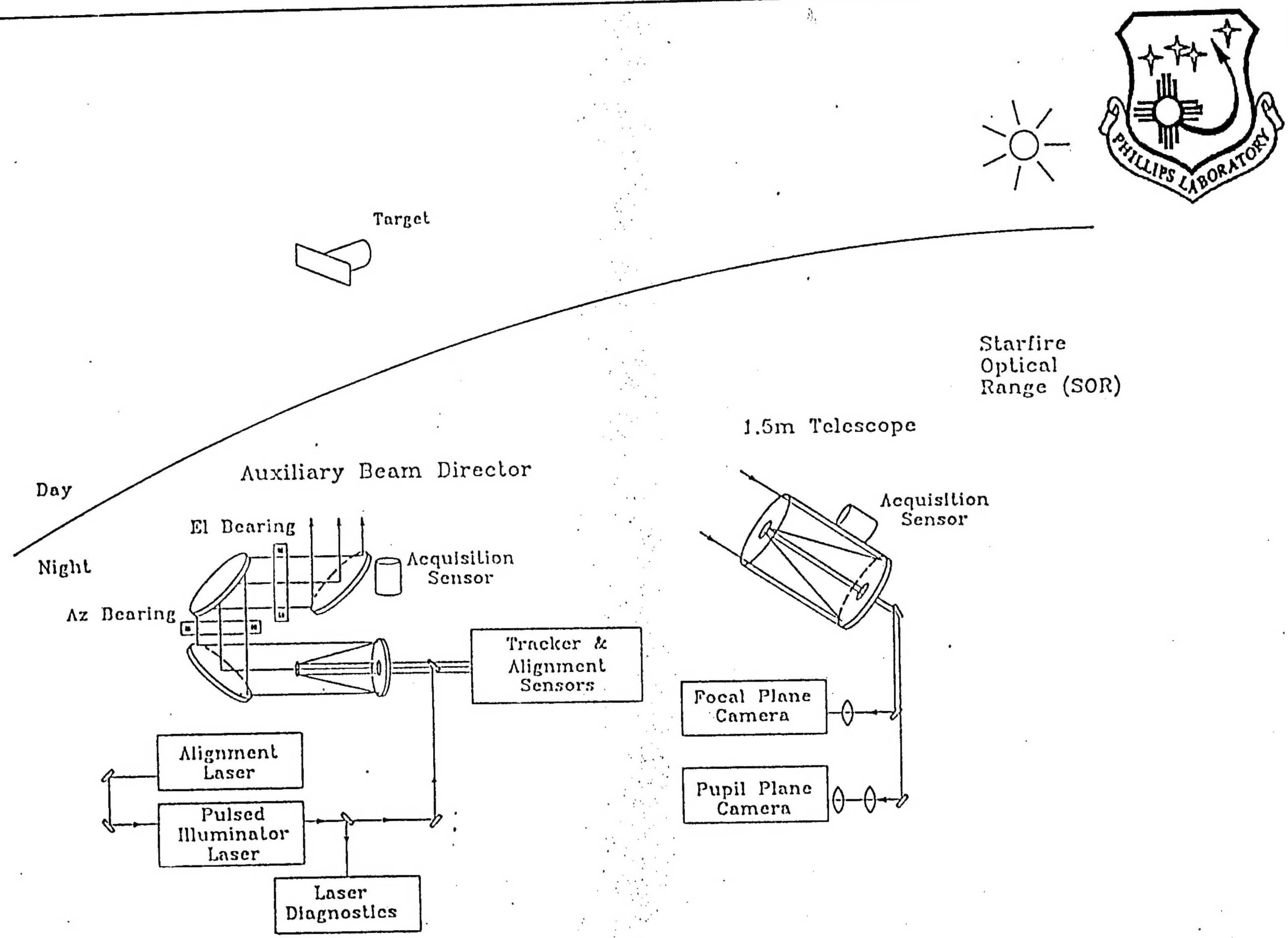


**Figure 1: Floodbeam Experiment Schematic**

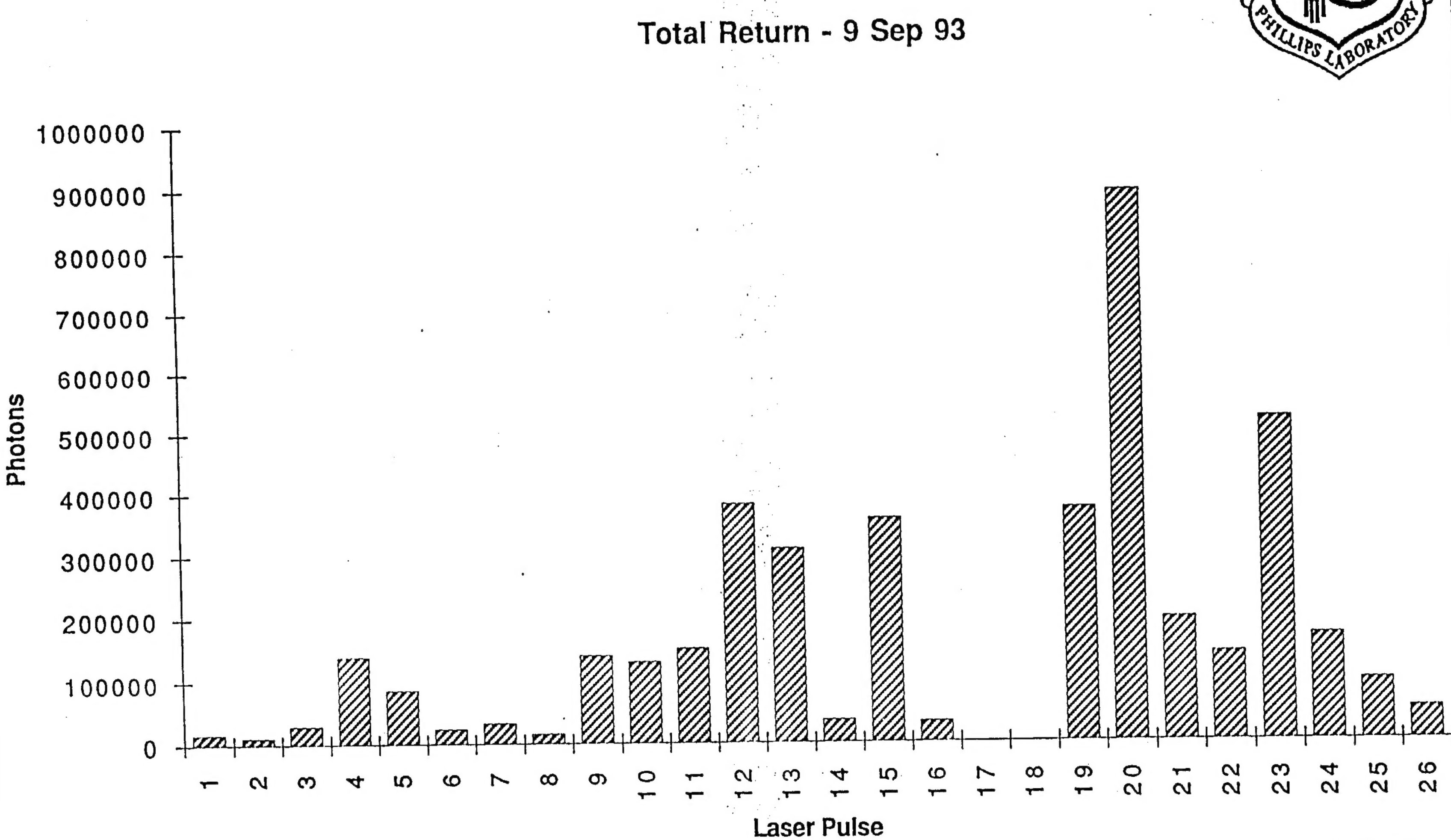


Figure 2: Total Photon Return from a Single Satellite Pass

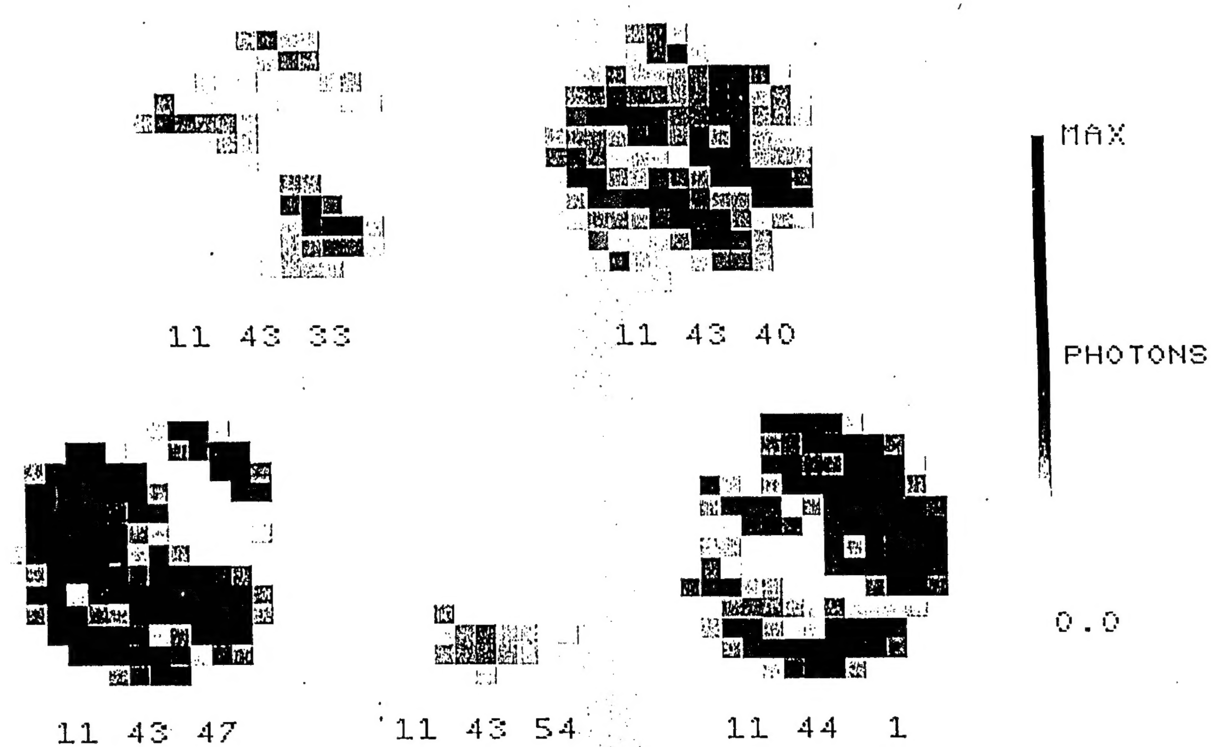


Figure 3: Five Consecutive Speckle Snapshots

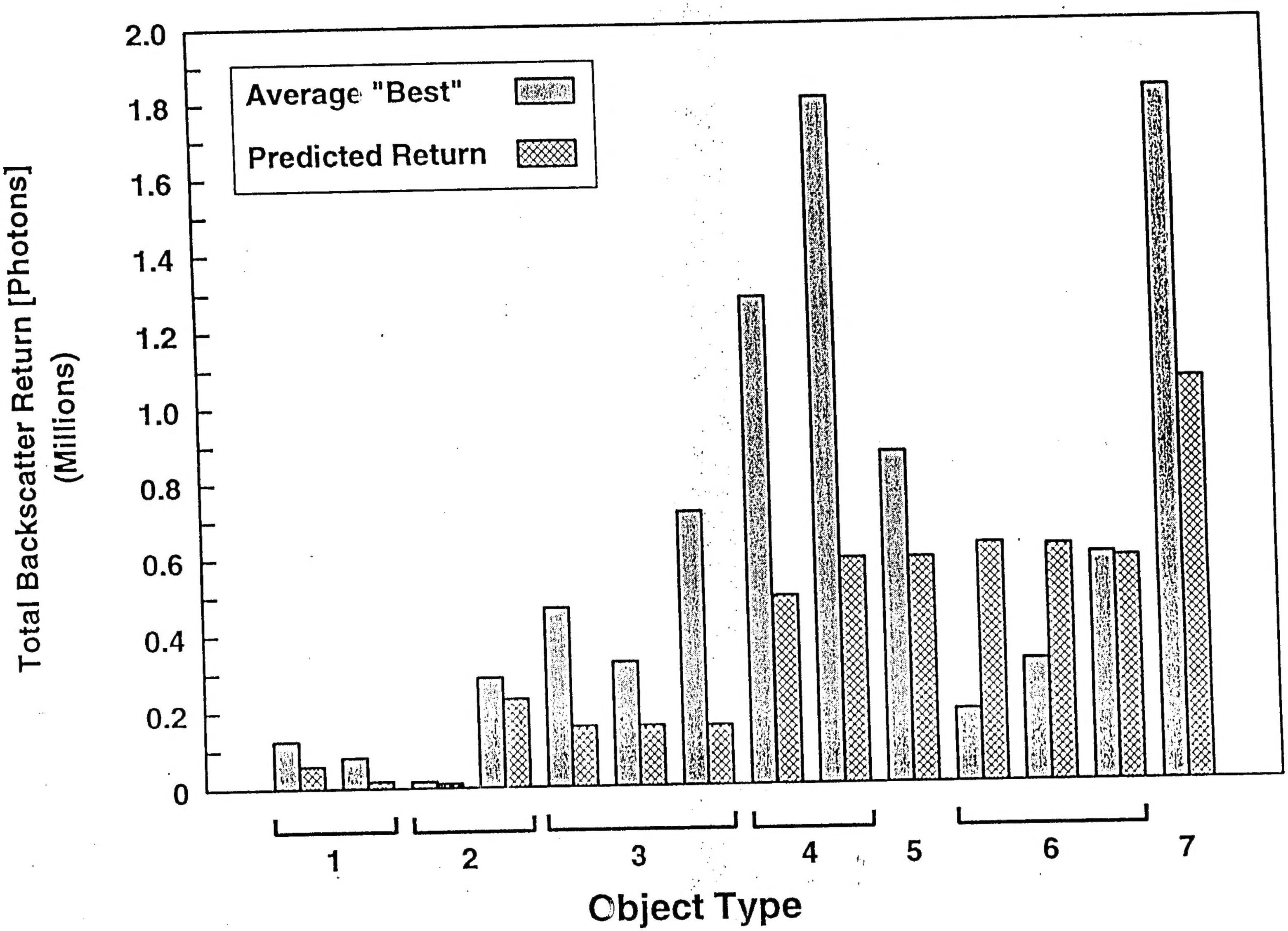


Figure 4 - Averaged "Best" Returns For Multiple Passes Normalized By Prediction